Economic valuation of natural predators for the biological pest control of *Cacopsylla pyri* in pear production, Belgium

1. Introduction

Biodiversity plays a key role in ecological processes and the delivery of ecosystem services, and its importance has been widely recognized (MA, 2005). In spite global actions, biodiversity is declining at an alarming rate (Butchart et al., 2012). In many cases, policy measures to safeguard biodiversity and resource developments are mutually exclusive and hence biodiversity conservation implies the decision to bear opportunity costs (Bennett et al., 2003). Being confronted with budget constraints, policy makers need to justify decision-making by supporting evidence of biodiversity benefits outweighing the opportunity costs incurred.

In 2001, the EU adopted the Biodiversity Action Plan, which aims at integrating environmental requirements into a market policy. In its mid-term assessment, the Commission confirmed the need for major action to stop the loss of biodiversity and acknowledged the need to strengthen independent scientific advice to global policy making (EC, 2008). But in spite the need for objectively comparable monetary standards to include biodiversity arguments in policymaking, the empirical literature investigating the relationship between species diversity and it's valuation from a farmers perspective is still scarce (Finger, 2015). On the one hand, the elicitation of values for biodiversity with the aid of stated preference methods is complicated due to the generally low level of awareness and understanding of what biodiversity means on the part of the general public (Christie et al., 2006). Furthermore, the willingness-to-pay (WTP) for species that are unfamiliar or undesired to the general public could yield extremely low values despite the fact that these species could be performing indispensible ecological services. On the other hand, revealed preference techniques have the advantage that they rely on the observation of peoples' actions in markets, however, the majority of species do not have a market price.

Therefore in this paper we introduce a methodological framework for the valuation of non-marketable species based on the ecological role of species in the agroecosystem to provide support for objective policy making outweighing the costs and benefits of biodiversity conservation. The framework integrates (i) a dynamic ecological model simulating interactions between species with (ii) an economic model integrating not only private costs but also external costs of a loss of species diversity. The model both (i) quantifies the contribution of biodiversity to the decrease in private and external costs in agroecosystems through the use of a production function technique, and (ii) attributes an objective monetary value to increased species diversity through the changes in the provisioning of a marketable good. The aim of the methodological framework is to provide quantifiable and objective measurements for the justification of biodiversity conservation through the delivery of verifiably comparable monetary standards which can be employed when considering trade-offs in policy making. The framework is applied for the presence of natural predators in pear production in Flanders

(Belgium) and the results reveal an objective value of three non-marketable species which provide biological pest control for the pest insect pear psylla (*Cacopsylla pyri*).

2. Methodology

2.1 Methodological framework

The methodological framework derives values for biodiversity based on the ecological role of species within the ecosystem whereby a change in biodiversity impacts the provisioning of a marketable good. The approach consists of integrating a dynamic stock and flow ecological model with feedback loops to represent the interaction between species with an economic model which consists of a private (CBA) and social cost benefit analysis (SCBA). Two linking functions connect the ecological and the economic model.

The dynamic ecological model is based on a production function technique whereby the biophysical relationship between biodiversity and marketable goods in the production process are used to infer values for the inputs, even when they are not marketed. It forms an essential part of the framework, since it objectively quantifies the benefits of biodiversity to humans, as compared to stated preference techniques which reveal beliefs rather than the functional role of species within the agroecosystem. The economic model takes into account both (i) the private costs for farmers and (ii) the increase in external costs which are attributed to the reduction in species diversity. The results reveal the contribution of biodiversity to the increase in market value of agricultural outputs and its contribution is traced back throughout the ecological-economic model built and this way infers the value of natural predators throughout the production process.

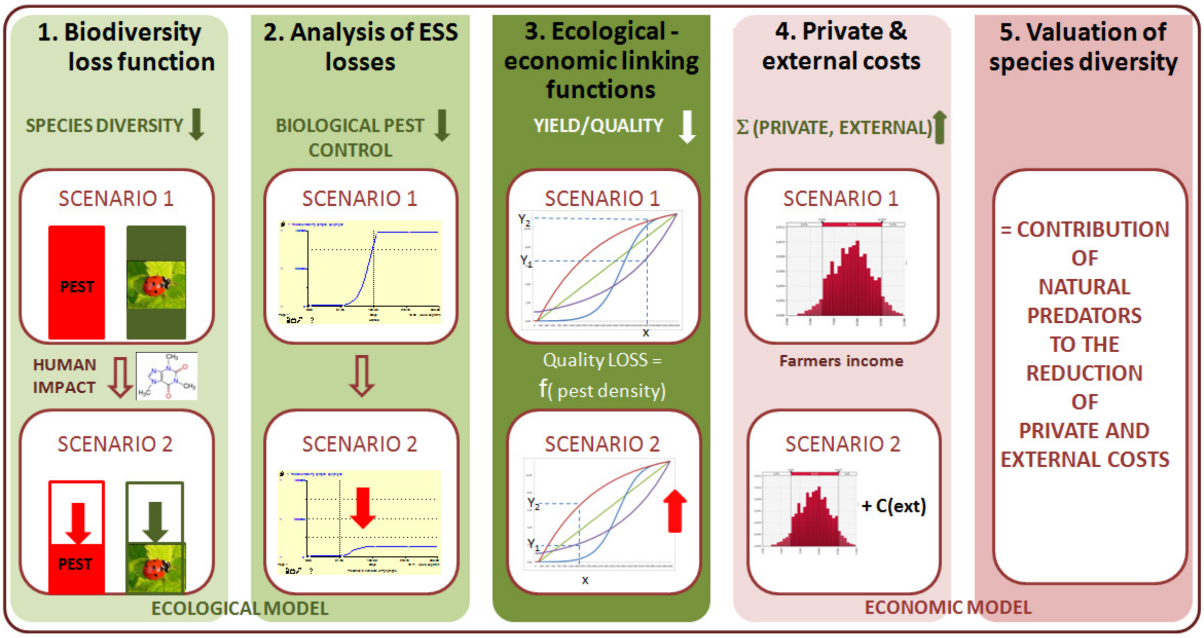

Figure 1: overview of the methodological framework with 1. The quantification of a biodiversity loss function for two scenarios (i) organic production and (ii) Integrated Pest Management (IPM). The loss of biodiversity in the IPM scenario is attributed to the application of insecticides; 2. The consequences of a reduction of biodiversity on ecosystem service delivery. The decrease in

natural predators results in a decrease in the provisioning of the biological pest control service; 3. The first ecological-economic linking function links the density of the pest insect to the level of crop damage incurred. The second linking function links the level of pesticide use to the external costs encountered; 4. The economic model includes the private and external costs of the scenario with and without insecticide use; 5. The valuation of non-marketable species. The value of natural predators is retraced throughout the model and is defined as the contribution of natural predators to the reduction of private and external costs for marketable output production.

2.1 Ecological model construction

The ecological model simulates predator-prey dynamics between the pest insect and three of its main natural enemies under two different management scenarios: (i) organic production and (ii) integrated pest management (IPM). Organic production constitutes the reference scenario and involves the absence of the use of insecticides for the control of the pest insect, thereby revealing a higher number of natural predators due to the absence of collateral damage effects of insecticides on natural predators, as compared to the IPM (alternative) scenario. First, a biodiversity loss function is calculated as the difference in species density levels for the two management scenarios. Second the loss in the ecosystem service biological pest control is quantified as the decrease in pest insects eliminated due to the reduction in the presence of natural predators.

2.1.1 Data collection

A total number of 113 field tests in low strain *conférence* pear production (7 in organic production and 104 in IPM) on 15 different plots (8 in IPM and 7 in organic production) are performed in Haspengouw (Belgium). Each field test sampled pear psylla eggs and nymphs on multiple days with a maximum of ten consecutive years of measurement (2004-2014). Data obtained from the plots under organic management were sampled in 2013 and 2014. Using the beating-tray method (3 beatings x 3 branches x 10 trees plot^{-1}), the nymph stages N1 to N5 are collected in a beating tray and counted (for a review of sampling methods see Jenser et al., 2010). A visual count is performed on newly developed shoot tips to assess the presence of eggs (visual counts are performed for 2 shoots per tree for 4-10 trees per plot segment with 4 plot segments per plot). Adult counts were performed sporadically with the beating-tray method but have not been included in the data due to its susceptibility to bias caused by adult mobility and the dependency on weather conditions. The mean counts of eggs per ten shoots are pooled for all consecutive years and plotted in figure 1.

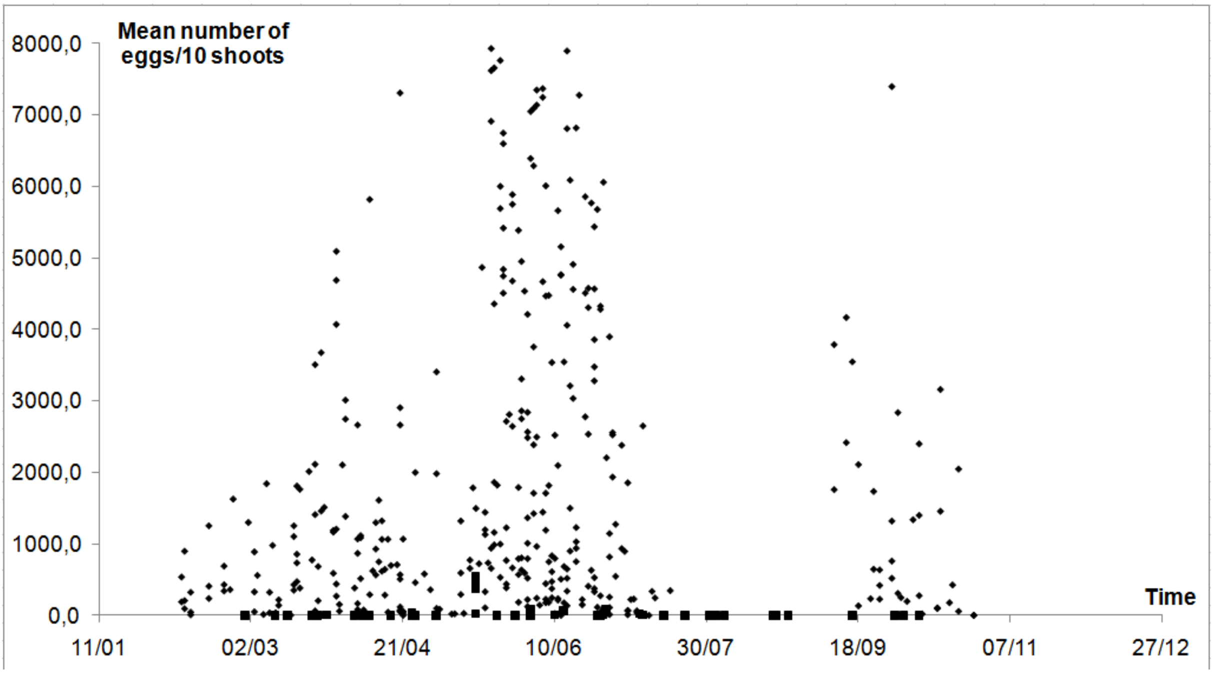

Figure 2: Pooled sample of mean numbers of pear psylla eggs per ten shoots collected between 2004 and 2014 (♦IPM; □ organic). Single fitted image.

In 2013 and 2014, counts for the presence of beneficial insects were been performed between February and Octobre in IPM and organic low strain *conference* pear plantations. Linear transects of three dug-in containers (r=0.2m) per 50m per pear row for three rows per plot were filled with water and detergent and left standing for 7 days. Emptying of the containers produced members of the order of the Aranea, Acari, Coleoptera, Hemiptera and Neuroptera. Figure 2 represents the pooled counts for a selection of the species in the samples collected based on the importance of their functional role as natural predators of pear psylla *Cacopsylla pyri* (Homoptera: psyliidae): *Anthocoris nemoralis* (Heteroptera: anthocoridae), *Allothrombidium fuliginosum* (Acari: trombidiidae) and *Heterotoma planicornis* (Hemiptera: miridae).

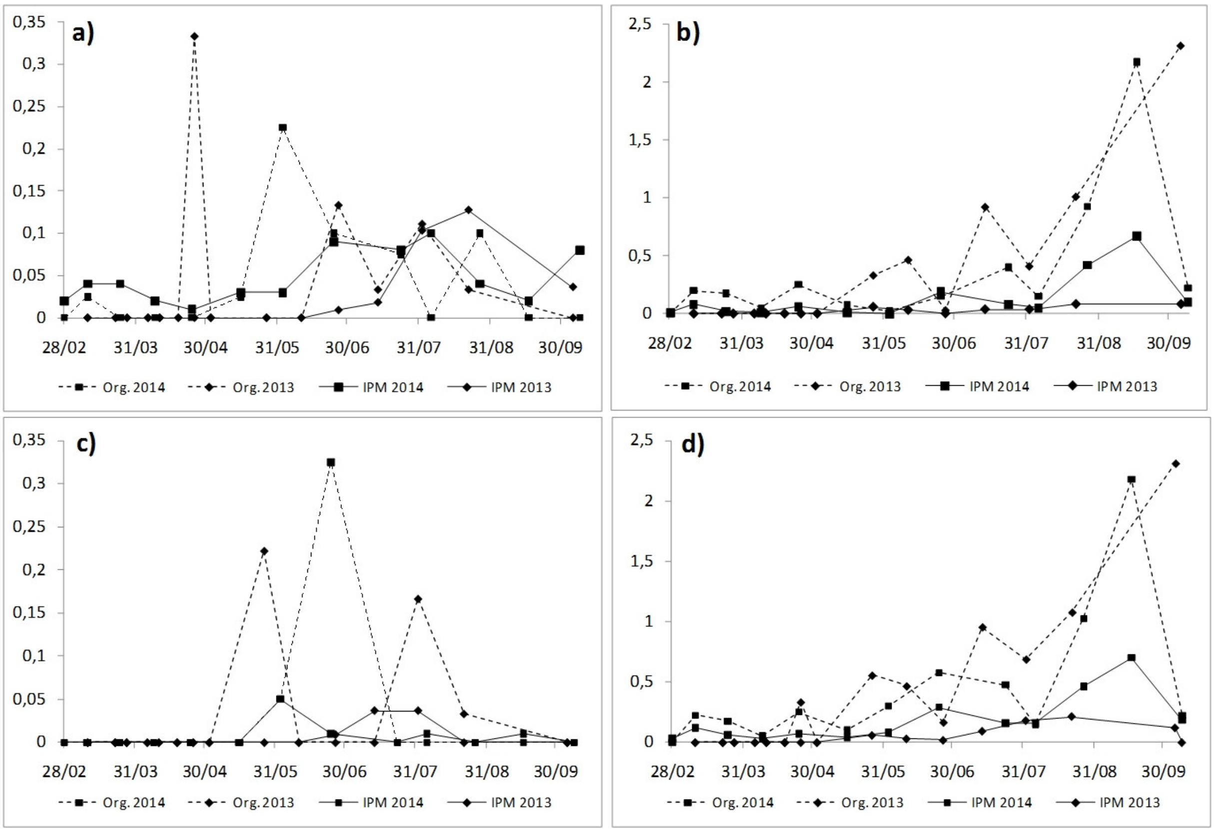

Figure 3: absolute number of individuals per sample for a) *Anthocoris nemoralis, b) Allothrombidium fuliginosum*, c) *Heterotoma planicornis* and d) sum of the absolute numbers of a, b and c. 2-column fitting image.

2.1.2 Scenario 1: organic production (SCENorg)

In the reference scenario for organic production (ORG_1) the biodemographics of a pest insect *Cacopsylla pyri* (Pp) and the interaction with three of its main natural predators (i) *Anthocoris nemoralis* (An), (ii) *Allothrombidium fuliginosum* (Af) and (iii) *Heterotoma planicornis* (Hp) (Erler, 2004) are simulated over a period of one year whereby:

$$dN_{Pp}/dt = f\left(N_{An}, N_{Af}, N_{Hp}\right) \qquad (1)$$

with N = species abundance. With the use of stella 10.0.6 (Stella; available at http://www.iseesystems.com) (Costanza and Gottlieb, 1998; Costanza and Voinov, 2001), the population dynamics of the four interacting species are simulated simultaneously. The selection of species has been verified through expert opinion and literature reviews. The main criteria employed for inclusion in the model is the importance of the species as main pear psylla antagonists. The initial model parameter values are represented in table 1. All parameters are allowed to vary on a daily basis.

Table 1

Model parameters for selected model components

	Parameter	Model component	Initial value (resp.)
(1)	Intitalisation adults	Ppa, Ana, Afa	1.8 * 106; 29520; 0.41*106
(2)	Initialisation eggs	Hpe	0.15 * 106
(3)	Female fraction	Ppa, Ana, Afa, Hpa	0.5
(4)	Loss fraction (eggs)	Ppe, Ane, Afe, Hpe	0.3; 0.4; 0.65; 0.6
(5)	Pp Food fraction	Ann, Afn, Hpn, Ana, Afa, Hpa	0.8;0.8;0.2;0.2;0.2;0.2
(6)	Predation fraction	Ann, Afn, Hpn, Ana, Afa, Hpa	0.6

Table 4: Initial parameter values for Pp, An, Af, Hp for eggs (e), nymps (n) and adults (a)

The food fractions (the fraction that Pp makes up in the daily diet) has been set for specialists at 0.8 (An) and for generalists (Af and Hp) at 0.2. The number of Ppe and Ppn preyed upon per day are variable and depending on prey density according to a logistic dependancy. The higher the density of Pp, the more Pp will be subject to predation as opposed to a linear dependency approach. Ovipositioning and longevity are non-constant parameters, depending on the time of the year and the adult generation cycle. It is assumed that Pp growth is not constrained by the use of resources and does not reach carrying capacity. Due to both predator activity (and resp. insecticide application for the alternative scenario), the Pp population does not reach abundance levels which are high enough in order for resource use to become a constraint. The growth function is modeled as a logistic growth curve, followed by a decline of the population.

Throughout the model, the effects of omitted species in the agroecosystem have been taken into account in two ways:

(i) An, Af and Hp are prey to ommitted species and this effect has been taken into account by the inclusion of a predation fraction for An, Af and Hp of 0.6.

(ii) An, Af and Hp have multiple food sources besides Pp which is represented in the model by setting the An, Af and Hp food fractions to vary between 0 and 1. The predation fractions therefore allow the predation of ommitted species.

2.1.3 Scenario 2: Integrated Pest Management (SCENipm)

In the reference scenario for Integrated Pesticide Management (IPM_1), the reference scenario for organic production is expanded with the introduction of insecticide applications. The timing (date), active ingredients applied and level of application (g/ha) are based on an exentensive dataset from 67 pear farmers over the period 2004-2014. The impact of consecutive insecticide applications (thiacloprid, Idoxacarb, fenoxycarb, spirodiclofen, abamectine, emamectine and rynaxypyr) is modeled as an immediate shock to the system, resulting in a death fraction as prescribed by ecotoxicological data.

Active ingredient	Pp_n	Pp_a	Af_n	Af_a	An_n	An_a	Hp_n	Hp_a
Thiacloprid	0.95	0.95	>0.75	>0.75	>0.75 *	>0.75 *	>0.75 *	>0.75 *
Indoxacarb	0.95	0.95	<0.25	<0.25	<0.25 *	<0.25 *	<0.25 *	<0.25 *
Fenoxycarb	0.95	0.95	0.5-0.75	<0.25	0.5-0.75 *	<0.25 *	0.5-0.75 *	<0.25 *
Spirodiclofen	0.95	0.95	0.25-0.5	<0.25	0.25-0.5 *	<0.25 *	0.25-0.5 *	<0.25 *
Abamectine	0.95	0.95	>0.75	>0.75	>0.75 *	>0.75 *	>0.75 *	>0.75 *
Emamectine	0.95	0.95	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *
Rynaxypyr	0.95	0.95	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *	<0.25 *

Table 5: The ecological toxicity of active ingredients on An_n and An_a. (*) Data not available. For Emamectine and rynaxypyr, a safe level for death fractions of 0.25 is assumed. The effects on An_n and An_a are extrapolated to Af_n, Af_a, Hp_n and Hp_a.

For Pp, all insecticide applications result in an instantaneous death fraction of 95% of the population. For An, Af and Hp, death fractions applied are represented in table 2. The percentages assumed for emamectine and rynaxypyr are based on policy prescriptions requiring all insecticides used as 'safe' for the environment whereby 'safe' means that the collateral damage to beneficial organisms is 25% or less.

2.1.4 Biodiversity loss functions

Within SCENorg and SCENipm there are 6 alternative models developed, each containing a different number of predators or a different combination of predators. The quantification of the loss of species diversity consists of analyzing two components: (i) species richness which is defined as the number of species and analysed within the alternative scenarios of SCENorg and SCENipm and (ii) the relative species abundance which describes the relative abundance of these species, and is analysed between the relevant SCENorg and SCENipm. Within both the organic management scenario (SCENorg) and the Integrated Pest Management scenario (SCENipm) different species richness levels are modelled for their effect on biological pest control. In doing so, the contribution of each of the individual species can be analysed. Between SCENorg and SCENipm the relative species abundance is analysed as the consequence of insecticide applications on the species abundance.

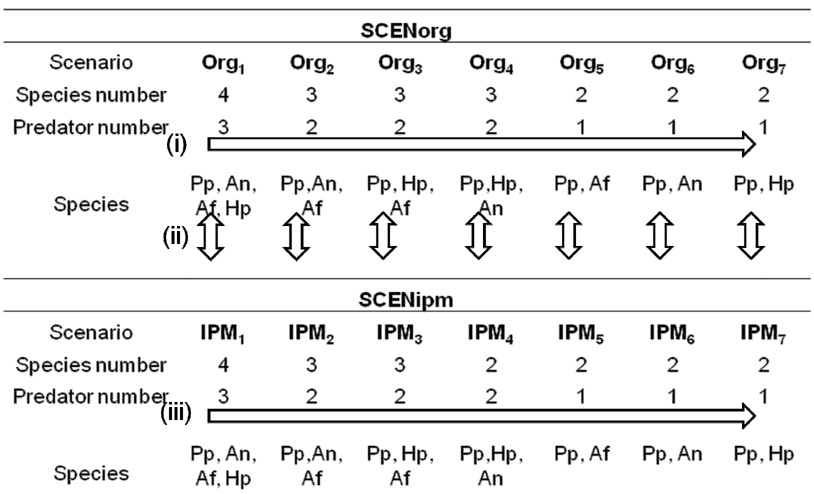

Table 6: (i) Species richness is modeled within scenario Org_1 to Org_7 and IPM_1 to IPM_7, (ii) the difference in relative species abundance is quantified for scenario pairs ORG_1 and IPM_1 to ORG_7 and IPM_7.

(i) $\% ORG_{within} = Pp(Org_x)/ Pp(Org_1) * 100$ (2)

(ii) $\% IPM - ORG = Pp(IPM_x)/ Pp(Org_x) * 100$ (3)

(iii) $\% IPM_{within} = Pp(IPM_x)/ Pp(IPM_1) * 100$ (4)

The model has not been constructed to allow for increases in natural predators abundance levels, when other natural predators competing for the same food source, decrease in numbers. Interdependancy between natural predators has not been modeled since the relationship between the pest insect and the natural predator is the main focus of the analysis and not the relationship between natural predators.

2.1.5 Quantification of biological pest control

With the aim of quantifying the biological pest control potential, the application of insecticides results in the decrease in the abundance of natural predators causing (i) a decrease in the number of pest insects consumed and (ii) an additional increase in pest insect abundance due to changing population dynamics. The relative loss of biological pest control (BPC) for Org_2 to Org_7, as compared to Org_1 is quantified as the sum of the increase I in the number of Pp_e and Pp_n and the decrease in Pp_e and Pp_n consumed C for a one-year period. Within SCENorg both the increase in Pp_e and Pp_n, as well as the decrease in Pp_e and Pp_n consumed are caused by a decrease in species richness for natural predators.

The sum of Pp_e, and Pp_n numbers is represented by $Pp_{en(x)}$. For all scenarios, the total biological pest control BPC_{tot} is equal to the total number of Pp consumed C_a

$$BPC_{tot} = C_a \quad (2)$$

The absolute loss in biological pest control BPC_{loss} for Org_2 to Org_7 as compared to Org1, is the sum of the increase Pp_I in the number of Pp_e and Pp_n and the decrease in Pp_e and Pp_n consumed C_{loss}

$$BPC_{loss} = \sum(C_{loss}, Pp_I) \text{ with} \quad (3)$$

$$C_{loss} = C_a - C_b \quad (4)$$

and $Pp_I = Pp_b - Pp_b$ (5)

The relative loss in biological pest control $BPC_{rel.loss}$for Org_2 to Org_7 as compared to Org1 is then

$$\frac{BPC_{loss}}{BPC_{tot\,(org1)}} \quad (6)$$

For the alternative scenarios within SCENipm, $Pp_I$is the result of both (i) a decrease in Pp_n due to the use of insecticides, as well as (ii) an increase in Pp_n and Pp_e due to the reduction in natural predators abundance levels as compared to the relevant SCENorg. For SCENorg, $PP_i = f\ (predators)$ whilst for SCENipm $PP_i = f\ (predators, insecticides)$

Therefore, the BPC_{tot} for the alternative SCENipm IPM$_2$ to IPM$_7$:

$BPC_{tot} = \sum(C_{loss}, Pp_{predators})$ with $C_{loss} = C_a - C_b$ and $Pp_{predators} = Pp_{insecticides} + Pp_I$

With $Pp_I = Pp_b - Pp_a$ (7)

The difference in BPC_{tot} between SCENorg and SCENipm is quantified according to:

$$BPC_{tot}ipm_x / BPC_{tot}organic_x \quad (8)$$

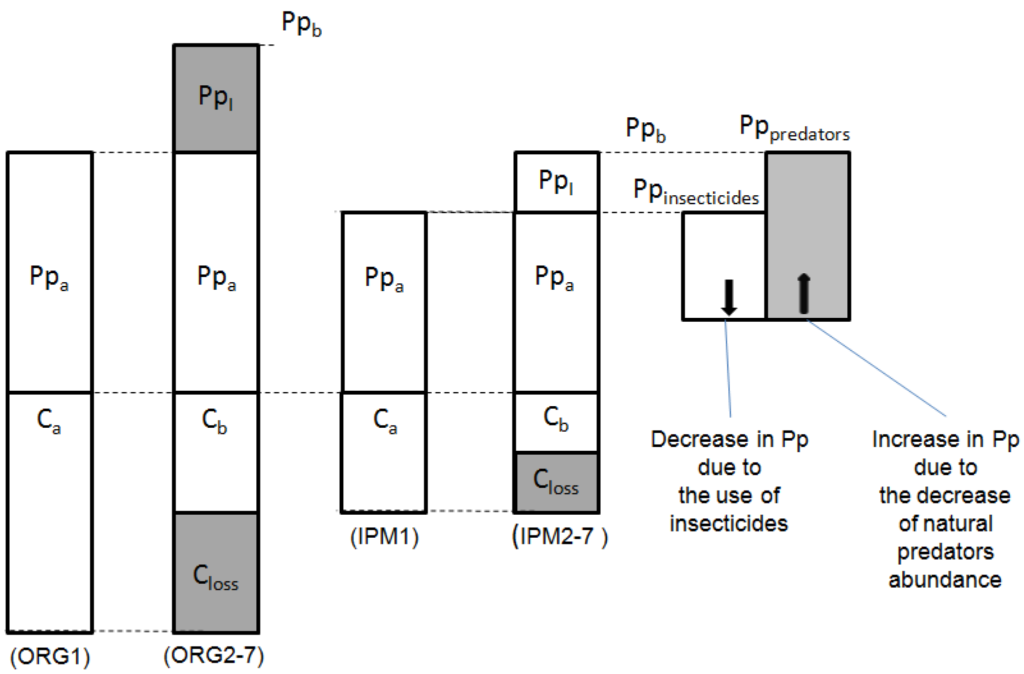

Figure 7: quantification of biological pest control for the reference scenarios (ORG$_1$ and IPM$_1$) and the alternative scenarios

2.3 Economic model construction

The economic model integrates not only private costs but also external costs of a loss of species diversity. The model both (i) quantifies the contribution of biodiversity to the decrease in private and external costs in agroecosystems through the use of a production function technique, and (ii) attributes an objective monetary value to increased species diversity through the changes in the provisioning of a marketable good.

2.3.1 Data collection

Accounting data on yields (kgha^{-1}), benefits (€ha^{-1}), variable costs and fixed costs at farm level for 70 farmers (67 IPM and 3 organic farmers) were collected during the period 2004-2014 and put to our disposal by the department of agriculture and fisheries of the Flemish government.

2.3.2 Private cost model

The economic model assesses (i) the private costs for SCENorg and SCENipm and (ii) the external costs incurred through the use of insecticides for SCENipm. The private profit maximization function is based on the damage control model for responsive applications by Lichtenberg and Zilberman (1986a) and is here defined as:

$$Max \prod_{p} = pg(Z) \int_{N1}^{N2} [1 - D(N, X(N), P(X))] \varphi(N) dN - \omega \int_{N1}^{N2} X(N)\, \varphi(N) dN - \tau Z(management) - m$$

The benefits are represented by the output price p multiplied by the realised yield $g(Z)$ whereby the yield damage D is a function of the pest population density N, the amount of insecticides applied $X(N)$ and the natural predator density $P(X)$. The private costs encountered are the costs τ with regards to input factors (labour and capital) Z, the cost of pesticide use ω which varies depending on the amount of pesticides applied $X(N)$ depending on the pest density level N_1 to N_2, and monitoring costs m. (For a full description see Lichtenberg and Zilberman, 1986a).

The effect of increased natural predator richness and relative natural predator abundance results in a decrease of pest density levels, causing a decrease in the level of insecticides required under responsive applications management. Lowering the amount of insecticides applied consequently lowers the external costs borne by society and rendering additional value to the presence of increased natural predators richness and abundance. Therefore, the Lichtenberg and Zilberman model is expanded with an inclusion of the external costs C_{ext} to take into account the monetary value of the impact of insecticides on human health and the environment.

$$C_{ext} = \vartheta \int_{X1}^{X2} C_{ext}\, \varphi(N) dN \quad \text{(a)}$$

with ϑ the quantity of pesticides used and C_{ext} the aggregated cost per unit of insecticides on human health and environment, varying for differing levels of pesticide use X_1 and X_2.

The social profit maximization function therefore becomes:

$$Max \prod_{p} = pg(Z) \int_{N1}^{N2} [1 - D(N, X(N), P(X))] \varphi(N) dN - \omega \int_{N1}^{N2} X(N)\, \varphi(N) dN - \vartheta \int_{X1}^{X2} C_{ext}\, \varphi(N) dN - \mu Z(management) - m \quad \text{(x)}$$

In the private cost model, the effect of the potential differences in the occurrence of black pears is analysed for its impact on (i) gross income and (ii) farm income.

The gross income I_G is defined as:

$I_G = \sum(I_b, I_r)$ (h)

where $I_b$represents the gross income from black pears:

$I_b = P_b * Q_b$ with $P_b$the price of black pears and Q_b the quantity of black pears (i)

and I_r the gross income of regular pears

$I_r = P_r * Q_r$ with $P_b$the price of black pears and Q_b the quantity of black pears (i)

The farm income is defined as

$I_F = I_G - TC$ (i)

with $TC = \sum(C_v, C_f)$ and TC the total costs, C_v the sum of the variable costs and $C_f$the sum of all fixed costs.

The accounting data are imported into the risk analysis tool Aramis (@risk) and all variables are allowed to vary in order to calculate a confidence interval for the farm income for all SCENorg and SCENipm. The difference in cost structure for SCENorg and SCENipm is mainly caused by the fact that IPM management shows (i) a higher yield (kgha^{-1}), (ii) a lower percentage of black pears, (iii) a higher cost for inputs (insecticides), (iiii) a lower amount of full-time equivalents (FTEs) for labour (eg. no manual weeding), (v) a lower price for pear products compared to organic pear prices.

2.3.3 External cost model

In the external cost model, first, the environmental impact of the use of insecticides on farm workers (applicators and pickers), consumers (ground water leaching and food consumption) and the environment (aquatic life, bees, birds) is combined in an environmental impact quotient. Next, the pesticide environmental accounting tool calculates the monetary value of the externalities.

2.4 Building an integrated dynamic ecological-economic model

Linking the ecological model with the economic model is established by two linking functions: (i) the damage threshold function that links the pest density level with the yield quality decrease and (ii) the pesticide environmental accounting function relates the use of insecticides with the of external costs to society (e.g. impacts on human health and environment).

2.4.1 Damage threshold function

The presence of the pest insect induces the presence of a sooty mold which becomes visible on the pears as a blackening of the skin, rendering them less valuable when sold on the market. Linking the density level of the pest insect with the economic damage it causes or, linking the biological pest control provided by the presence of natural predators with the economic costs avoided, requires analyzing the relationship between pest insect density and the reduction in quality. The damage control function links the density of the pest insect (adult days/ha) to the yield loss (% black pears occuring). As a general guideline it is recommended by governmental authorities that when monitoring the pest insect reveals a density which is larger than 1000 adults per 10 beatings, action (insecticide application) is allowed because a not further specified 'detectable damage' will be incurred. Recalculating 1000 adults per 10 beatings into numbers per ha results in the presence of a minimum of $386*10^6$ adults/ha yield to yield 'detectable damage'. Since it is assumed that farmers are maximizing profits, 'detectable damage' is translated into the lowest amount of black pears that is desired (<1%). Fixating this value at 1% equally fixes the maximum percentage of black pears (at maximum pest density). Therefore a second damage threshold function (high impact damage function) is constructed for which the maximum percentage of black pears obtainable is 100%. Since the shape of the damage control function is not known, four hypothesized relationships were constructed to simulate the correlation between Pp_a density levels δ_{ppa} ($ha^{-1}y^{-1}$) and black pear occurrence γ (%):

(i) Linear: $\gamma_{lin} = \alpha\, \partial_{Ppa}$ with $\alpha = 0.0026$ (10)

(ii) Logistic: $\gamma_S = \frac{k}{(1+(k-\partial_0/\partial_0)} * exp^{r\partial_{Ppa}}$ (11)

with k (stable value) = 11.66 (max of the linear function), ∂_0(initial value) = 0.01 and r (rate) = $k/\max_{\partial ppa}$ and $max_{\partial ppa}$ = 4500

(iii) Logarithm: $\gamma_{log} = 1 - exp^{-\partial_{ppa}}$ (12)

(iv) Exponential: $\gamma_{exp} = exp^{\partial_{ppa}}$ (13)

This results in a lower bound γ_l and upper bound γ_u for both the low impact model and high impact model for all SCENorg and SCENipm with:

$$\gamma_l = \min(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp}) \text{ and } \gamma_u = \max(\gamma_{lin}, \gamma_S, \gamma_{log}, \gamma_{exp}) \quad (14)$$

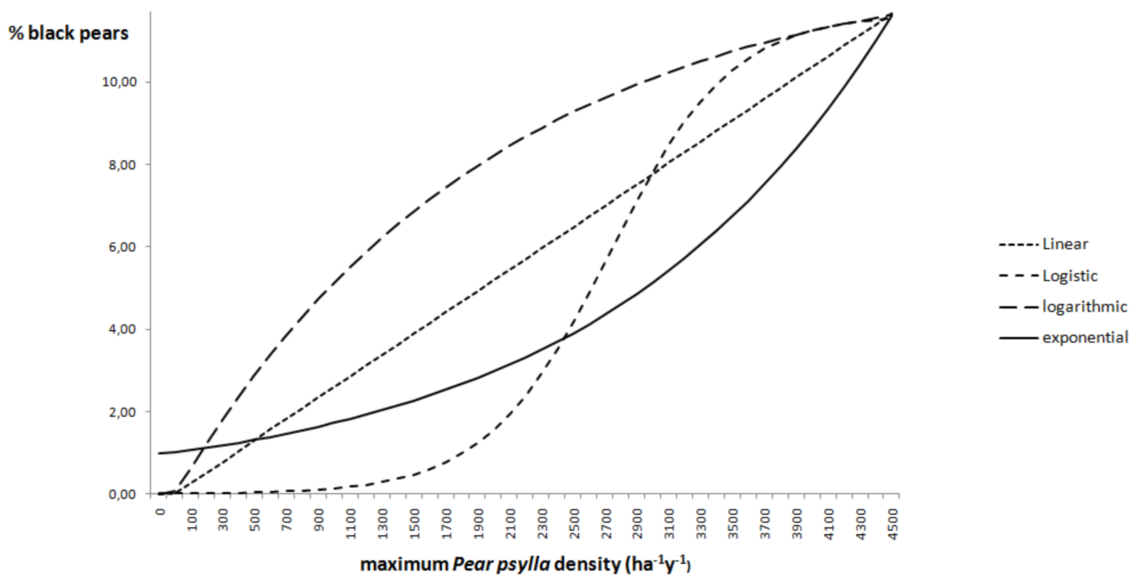

Figure 8: (Low impact damage function). The damage threshold function relates the maximum Pp density which is observed to the percentage of black pears that could be expected, based on four hypothesized correlations (a) linear, (b) logistic, (c) logarithmic and (d) exponential.

2.4.2 External cost function for insecticide application

The presence of natural enemies reduces the number of pest insects, and therefore also reduces the amount of insecticides which needs to be applied. Hence, the presence of natural predators indirectly reduces the external costs associated with the use of pesticides. A large number of surveys have been published, revealing the external costs to society of pesticide application (Pimentel et al., 1993), eg. the effects of pesticide application on public health, groundwater contamination, and fishery losses. However, for this analysis it is not the total effect of all pesticides used that is modeled and therefore the link between external costs and the level and use of specific insecticides is analyzed through the use of the pesticide environmental accounting tool (Leach and Mumford, 2008). The tool calculates the total economic costs of a specific insecticide applied taking into account the effect on farm workers (applicators and pickers), consumers (ground water leaching and food consumption) and the environment (aquatic life, bees and birds).

3. Results

3.1 Species richness and relative species abundance

The effect of consecutive insecticide applications on species abundance for Pp in SCENIPM1 as compared to SCENORG1 reveals an overall decrease in abundance of 45.73 % (table 10). A significant decrease in pest numbers was expected. The population dynamics of Ppe, Ppn, Ppa, Afa, Ana and Afa for SCENorg1 (left) and SCENipm1 (right) are represented in figure 9.

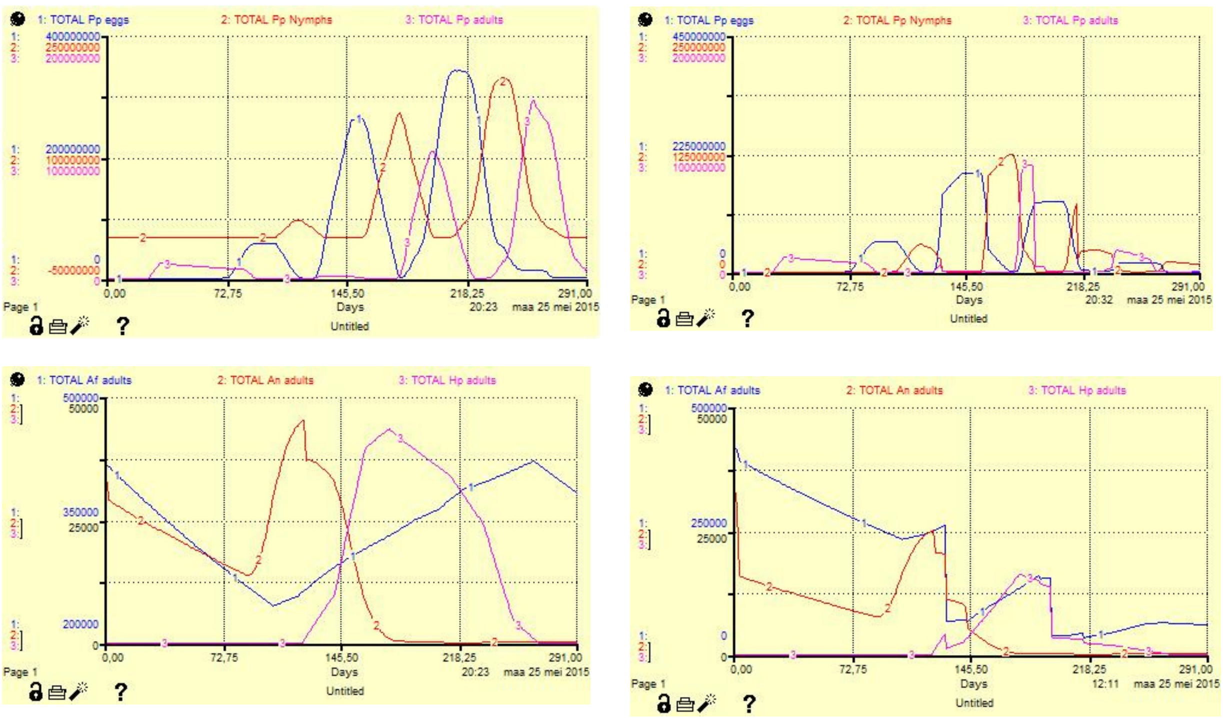

Figure 9: shows the number of individuals for a one year period for SCENORG1 (left hand side) and SCENIPM1 (right hand side). Top left (resp. right): numbers of pear psylla eggs (blue), nymphs (orange) and adults (pink). Bottom left (resp. right) population dynamics for Af adults (blue), An adults (red) and Hp adults (pink). The sharp decreases in population numbers in the bottom right graph are due to the application of insecticides at that time.

The reduction in the species richness of natural predators for SCENorg1 to SCENorg7 reveals an increase in Pp adult numbers with a factor to 2.06 to 19.31 according to equation (2). Due to the use of insecticides the difference between $SCENorg_x$ and $SCENipm_x$ for the same natural predator species richness results in losses between 45.73 % and 95.34% according to equation (3). The % increases in Pp for SCENipm remain within a narrower range of between factor 1 and 2.78 according to equation (4).

SCENORG	Org_1	Org_2	Org_3	Org_4	Org_5	Org_6	Org_7
Species richness	4	3	3	3	2	2	2
Predator richness	3	2	2	2	1	1	1
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp
Pp (x 10^6)	1237	2551	8130	12633	10905	16005	23888
% ORG_{within}		206	657	1021	882	1294	1931
SCENIPM	IPM_1	IPM_2	IPM_3	IPM_4	IPM_5	IPM_6	IPM_7
Species richness	4	3	3	2	2	2	2
Predator richness	3	2	2	2	1	1	1
Species	Pp, An, Af, Hp	Pp,An, Af	Pp, Hp, Af	Pp,Hp, An	Pp, Af	Pp, An	Pp, Hp
Pp (x 10^6)	671	671	791	1623	791	746	1872
% IPM-ORG	-45.73	-73.68	-90.27	-87.16	-92.75	-95.34	-92.16
% IPM_{within}		100.00	117.79	241.69	117.79	111.16	278.78

Table10: (upper) Increases in Pp adult abundance due to the reduction in natural predators species richness, (lower) Decreases in Pp adult abundance due to insecticide use.

Species abundance levels for natural predators in SCENIPM1 decrease significantly. The decrease in total predator numbers leads up to between 33,9% (Af) and 57.9 % (Hp) (table 11). A 'safe' scenario (SCENsafe) has been simulated in order to test the effect of consecutive insecticide applications and timings on predators' abundance. All death rates has been set to 0.25 to represent the safe level of collateral damage. Results show that when population dynamics are taken into account, total losses in all cases account for >25% and range between 25.10% (An_n) and 43.95% (Af_a).

	SCENORG	SCENIPM	% loss	SCEN safe	% loss
Afn	803196	530423	33.96	496097	38.23
Afa	412826	233430	43.46	231371	43.95
Ann	59144	32444	45.14	44301	25.10
Ana	40587	22096	45.56	30284	25.38
Hpn	94020	94020	0.00	94020	0.00
Hpa	51296	21591	57.91	34846	32.07

Table11: Losses in relative species abundance for natural predators for SCENoprg, SCENipm (death rates according to table 5) and SCENsafe (all death rates equal 0.25) to account for the effect of consecutive insecticide applications and timings.

3.2 Biological pest control (BPC) losses

A cumulative graph of BPC_{tot} for SCENorg1 as compared to SCENipm1 shows a substantial difference between biological pest control under organic management as compared to IPM. Results reveal that for the loss of the first predator, the BPC_{tot} of IPM management drops to between 0.71% and 75.02% as compared to organic management, and to between 7.54% and 84.87% with the loss of the second predator.

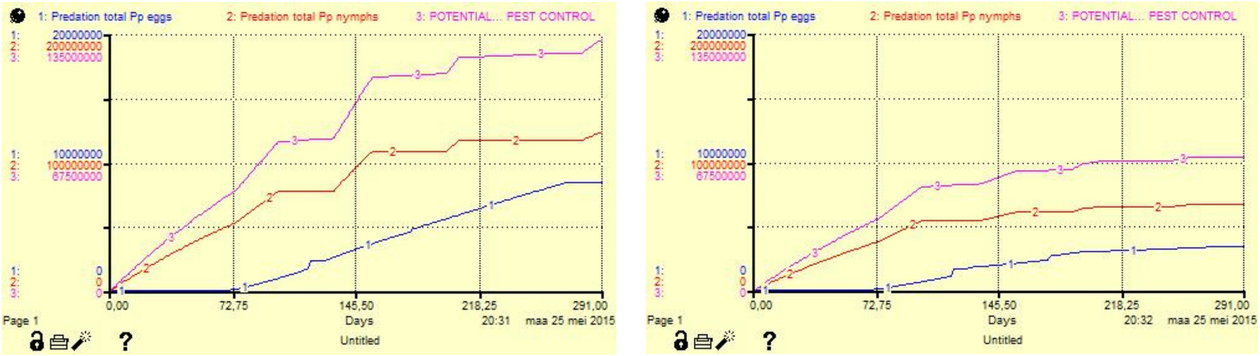

Figure 12: total number of pest insect nymphs removed by natural predators for the reference scenario (a) and the alternative scenario (b) for a period of one year

SCENipm	Pred.	$BPC_{totorg(x)}/BPC_{totipm(x)}$
IPM1/ORG1	3	52.60
IPM2/ORG2	2	61.46
IPM3/ORG3	2	75.02
IPM4/ORG4	2	0.71
IPM5/ORG5	1	84.87
IPM6/ORG6	1	7.54
IPM7/ORG7	1	49.97

Table 13: The difference in BPC_{tot} between SCENorg and SCENipm

However, assessing the total loss of BPC_{tot} requires taking into account the changes in Pp abundance, as well as the changes in BPC_{tot}. For SCENorg, the absolute loss of biological pest control due to the reduction in natural predators species richness has been calculated as the sum of decrease in predation (Ppe and Ppn consumed) and the increase in Ppn and Ppa. With a reduction in the number of predators from 3 to 2, the potential loss in BPC increases substantially with a factor between 10 to 84 times as compared to the BPC provided by 3 predators. An additional loss of a predator species decreases the BPC with a factor 73 to 171. Equally so, the absolute BPC_{tot} relative to the absolute pest insect numbers, reduces from 10.72% for the presence of three predators, to between 4.45% and 1.08% for 2 predators, and decreases further to between 0.71% and 0.02% for the presence of only one predator.

SCENorg	Pred.	$Pp_{en(x)}$ x 10^6	BPC_{tot} x 10^6	Pp_l x 10^6	C_{loss} x10^6	BPC_{loss} x10^6	$BPC_{rel. loss}$	$BPC_{tot}/Pp_{en(x)}$
ORG1	3	1237.11	132.59					10.72
ORG2	2	2550.87	113.43	1313.77	19.16	1332.92	10.05	4.45
ORG3	2	8130.10	87.89	6893.00	44.70	6937.69	52.32	1.08

ORG4	2	12632.92	290.05	11395.81	-157.46	11238.36	84.76	2.30
ORG5	1	10905.15	77.66	9668.04	54.93	9722.97	73.33	0.71
ORG6	1	16005.04	27.04	14767.93	105.55	14873.48	112.18	0.17
ORG7	1	23888.50	4.00	22651.39	128.59	22779.98	171.81	0.02

Table 14: Absolute and relative losses for biological pest control of SCENorg as compared to SCENorg1.

Alternatively, for SCENipm, the potential loss in BPC increases with a factor 19 to 99 as compared to the BPC provided by three predators and with a factor 84 to 125 for the additional loss of a predator γthe presence of three predators, to between 10.38% and 0.13% for 2 predators, and decreases further to between 8.33% and 0.11% for the presence of only one predator.

SCENipm	Pred.	$Pp_{en(x)}$ x 10^6	BPC_{tot} x 10^6	Pp_I x 10^6	$Pp_{insecticides}$ x10^6	C_{loss} x10^6	BPC_{loss} x10^6	$BPC_{rel.\ loss}$	$BPC_{tot}/Pp_{en(x)}$
IPM1	3	671.39	69.74						10.39
IPM2	2	671.37	69.72	-0.02	4412.31	0.03	4412.33	63.26	10.38
IPM3	2	790.86	65.94	119.47	1384.39	3.81	1388.20	19.90	8.34
IPM4	2	1622.69	2.05	951.30	6856.04	67.70	6923.74	99.27	0.13
IPM5	1	790.85	65.91	119.45	5918.36	3.83	5922.19	84.91	8.33
IPM6	1	746.33	2.04	74.94	12964.58	67.71	13032.28	186.86	0.27
IPM7	1	1871.74	2.00	1200.34	8686.13	67.74	8753.87	125.51	0.11

Table 15: Absolute and relative losses for biological pest control of SCENipm as compared to SCENipm1.

3.3 Correlation between pest insect density and crop damage

For each scenario, the maximum pest density δ_{ppa} ($ha^{-1}y^{-1}$) was obtained. The correlation between δ_{ppa} and the percentage of black pears γ for the four hypothesized relationships γ_{lin}, γ_S, γ_{log}, $\gamma_{exp}$are represented in table 14. On the one hand, the low impact function assumes a profit maximization principle and therefore, the economic threshold level is set at 1% black pears. Due to the linear character of γ_{lin}, the potential maximum for γ equals 11.28%. On the other hand, the high impact damage function assumes that in reality, the possibility of γ reaching 100% is possible at maximum values of δ_{ppa}.

Low impact damage function

Model	δ_{Ppa} ($10^6 ha^{-1}$)	γ_{lin} (%)	γ_S (%)	γ_{log} (%)	γ_{exp} (%)	γ_l (%)	γ_u (%)
IPM1	91.5455	0.24	0.01	0.58	1.05	0.01	1.05
IPM2	91.5455	0.24	0.01	0.58	1.05	0.01	1.05
IPM3	111.1770	0.29	0.01	0.70	1.06	0.01	1.06
IPM5	111.1784	0.29	0.01	0.70	1.06	0.01	1.06
ORG1	146.9157	0.38	0.01	0.92	1.08	0.01	1.08
IPM4	247.8209	0.64	0.02	1.52	1.14	0.02	1.52
IPM6	247.8257	0.64	0.02	1.52	1.14	0.02	1.52
IPM7	283.5866	0.73	0.02	1.72	1.17	0.02	1.72
ORG2	379.7750	0.98	0.03	2.25	1.23	0.03	2.25
ETL*	386.0000	1.00	0.03	2.28	1.23	0.03	2.28
ORG3	1331.6776	29.59	0.31	6.32	2.07	0.31	6.32

ORG5	1815.2014	4.70	1.01	7.75	2.69	1.01	7.75
ORG4	2134.8315	47.44	2.08	8.53	3.20	2.08	8.53
ORG6	2714.9748	7.03	5.76	9.66	4.39	4.39	9.66
ORG5	4036.5474	89.70	11.28	11.27	9.02	9.02	11.28

High impact damage function

Model	δ_{Ppa} (10^6ha^{-1})	γ_{lin}	γ_S	γ_{log}	γ_{exp}	$\gamma_{l\,(\%)}$	$\gamma_{u\,(\%)}$
IPM1	91.5455	2.03	0.65	8.75	1.10	0.65	8.75
IPM2	91.5455	2.03	0.65	8.75	1.10	0.65	8.75
IPM3	111.1770	2.47	0.69	10.52	1.12	0.69	10.52
IPM5	111.1784	2.47	0.69	10.52	1.12	0.69	10.52
ORG1	146.9157	3.26	0.77	13.66	1.16	0.77	13.66
IPM4	247.8209	5.51	1.04	21.95	1.28	1.04	21.95
IPM6	247.8257	5.51	1.04	21.95	1.28	1.04	21.95
IPM7	283.5866	6.30	1.16	24.69	1.33	1.16	24.69
ORG2	379.7750	8.44	1.54	31.60	1.46	1.46	31.60
ETL*	386.0000	8.58	1.57	32.02	1.47	1.47	32.02
ORG3	1331.6776	29.59	21.36	73.60	3.79	3.79	73.60
ORG5	1815.2014	40.34	53.68	83.72	6.14	6.14	83.72
ORG4	2134.8315	47.44	75.14	88.17	8.46	8.46	88.17
ORG6	2714.9748	60.33	94.51	93.38	15.10	15.10	94.51
ORG5	4036.5474	89.70	99.89	98.23	56.63	56.63	99.89

Table 16: Lower and upper values for the percentage of black pears for changing pest density levels.(* ETL = Economic Treshold Level). Top: the low impact damage function assumes the ETL is reached at 1% black pears. Bottom: the high impact damage model assumes 100% black pears at maximum pest density levels.

The results reveal that all SCENipm remain under the economic threshold level (ETL) whilst the majority of SCENorg are above the ETL. The only exceptions are ORG_1 which is the most plausible since it is the model with the highest species richness for natural predators and ORG_2. It is questionable whether ORG2 in fact is significantly different from the ETL and this reveals the importance of the presence of multiple predators to avoid economic damage to occur.

The low impact damage scenario shows damage levels between 0.01% and 1.72% (resp.0.01 %and 11.28%) for SCENipm (resp. SCENorg). The high impact damage scenario reveals damage levels between 0.65% and 24.69% (resp. 1.46% and 99.89%) for SCENipm (resp. SCENorg).

3.4 Economic impact of a reduction in species diversity on gross income

Selling prices for 1st class, 2nd class and organic pears were obtained for the period 2009-2013. The average selling price for all years for non-organic pears was 0.57 €kg^{-1} with $\mu_1 = 0.70$, μ_2= 0.39, μ_3= 0.88 with s_1= 0.15, s_2= 0.12, s_3= 0.17 n_1=20, n_2=15, n_2=15 resulting in a 95% confidence interval for 1st class pears (resp. 2nd class pears; organic pears) of [0.63;0.78] (resp.[0.32;0.46];[0.78;0.97]). The gross income for SCENorg for the low impact damage function (resp. high impact damage function) ranged between 29282 €ha^{-1} and 30577 €ha^{-1} (resp.20101 €ha^{-1} and 29678 €ha^{-1}) and between 24427 €ha^{-1} and 24463 €ha^{-1} (resp.23125 €ha^{-1} and 24013 €ha^{-1}) for SCENipm. The low impact scenario reveals losses between 0.26% and 2.10% (resp. 0.001% and 0.1%) for SCENorg (resp. SCENipm) the reduction from 3 to 2 natural predators, and between 1.69% and 4.23% (0.002% and 2.15%) for SCENorg (resp. SCENipm) for a reduction from 2 to 1 predator. For the high impact scenario, losses between 4.23% and 18.67% (resp. 0.001% and 3.06%) for SCENorg (resp. SCENipm) the reduction from 3 to 2 natural predators, and between 17.13% and 32.27% (resp. 0.41% and 3.70%) for SCENorg (resp. SCENipm) for a reduction from 2 to 1 predator. The low impact scenario reveals that the value of a decrease in species richness for SCENorg (resp. SCENipm) ranges from 79 to 641 €ha^{-1} (resp. 1 to 25 €ha^{-1}) for a reduction from 3 to 2 predators and from 517 to 1295 €ha^{-1} (resp. 1 to 36 €ha^{-1}) for the a reduction from 2 to one predator, whilst the high impact scenario reveals that the value of a decrease in species richness for SCENorg (resp. SCENipm) ranges from 1256 to 5540 €ha^{-1} (1 to 734 €ha^{-1}) for a reduction from 3 to 2 predators and from 5084 to 9576 €ha^{-1} (98 to 888 €ha^{-1}) for the a reduction from 2 to one predator .

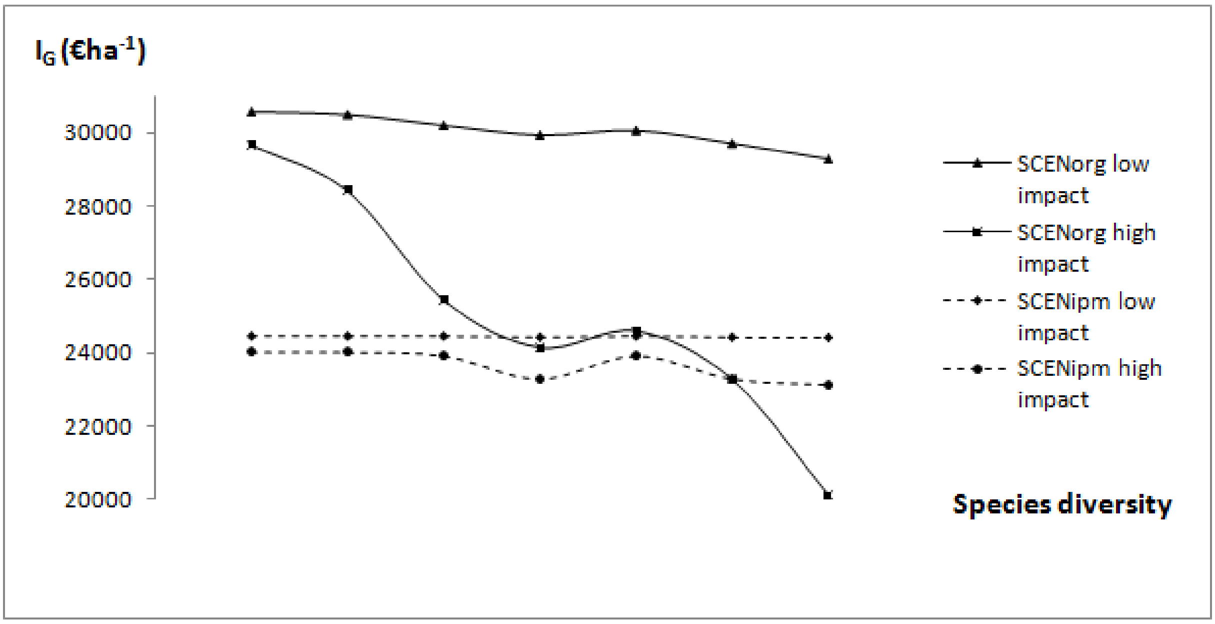

Figure 17: The effect of a loss of species diversity on the gross income (€ha^{-1})

The value of the loss in species abundance is represented by the average difference in gross income between SCENorg and SCENipm and ranges between 19.55% reduction in gross income (IPM_1/ORG_1) or 5889 €ha^{-1} to 3.71% (IPM_7/ORG_7) or 915 €ha^{-1} .

The intermediary results indicate a higher dependency for organic farming on the presence of natural predators with the possibility of a significantly higher gross income, provided that enough natural predators remain in the agroecosystem. Gross income for SCENipm is on average significantly lower than for SCENorg for all levels of species diversity but is less vulnerable to changes in species diversity. The decrease in variability results from the decrease in the presence of *Pear psylla* and hence a lower percentage of black pears. It should be noted that based on the gross income, it cannot be concluded that the use of insecticides reduces risk in pear production, as is shown later on (see discussion). Furthermore, it is expected that the inclusion of external costs in the framework will significantly affect the results.

3.5 Economic impact of a reduction in species diversity on farm income

When assessing the effects of a decrease in species diversity on income, not only the difference in gross income (yield and prices) is taken into account but also the differences in cost structure with regards to e.g. inputs used. Descriptive statistics show that: 1) the amount of non-consumable pears sold as feed is on average 20% less for organic production, due to lower yields in total (μ_{ipm}=458.25 kgha^{-1}, μ_{org}= 366.60 kgha^{-1}), 2) organic farmers can on average claim 52% higher subsidies (μ_{ipm}= 138.61 €ha^{-1}, μ_{org}= 210 €ha^{-1}), 3) Crop protection for IPM accounts for 1650 €ha^{-1}, for organic production, no costs have been taken into account and 4) organic management requires 30% more labour (μ_{ipm}= 4270.70 €ha^{-1}, μ_{org}= 5789.17 €ha^{-1}). For reasons of simplicity, other production factors (e.g. conservations costs, maintenance, packaging) are assumed equal for both scenarios.

The first results of a decrease in species abundance on farm income are of comparable magnitude to the gross income decreases. A comparison between SCENorg and SCENipm yields on average 14498.81 €ha^{-1} for Org_1 and 12525.27 €ha^{-1} for IPM1, resulting in a loss of 1973.54 €ha^{-1}.

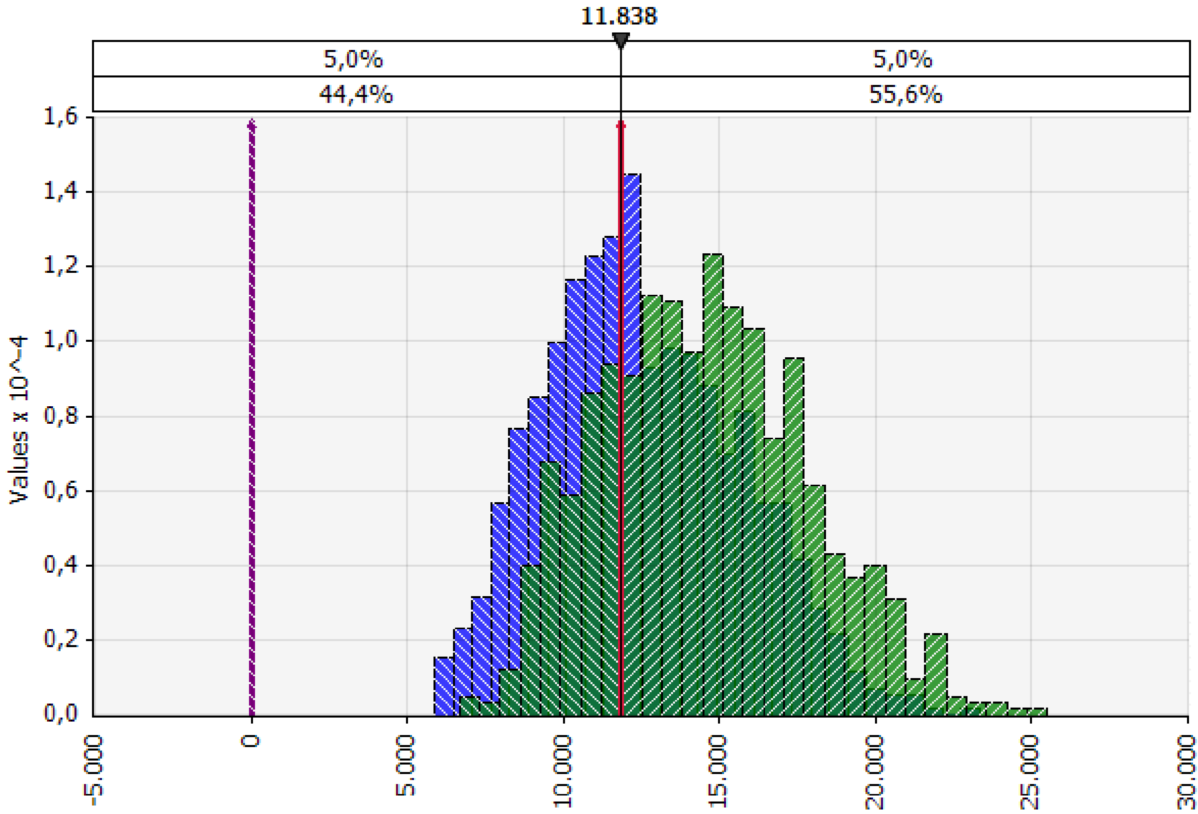

Figure 18: 95% confidence intervals for the difference farm income due to the loss in species abundance.

All results for the other scenarios are expected within the next week.

4. Discussion

Preliminary results show that a decrease in relative species diversity or species abundance can result in significant losses, both in terms of gross income losses as well as farm income losses. Furthermore, these results are expected to be conservative estimates due to several reasons:

(i) the death fractions of natural predators employed in the ecological model are only the minimal death fractions that have been reported in ecotoxicological data

(ii) the duration of action of insecticides is assumed to be one day, while in reality the duration of insecticides will be more and therefore cause higher death rates for natural predators

(iii) the additional benefits of increased diversity on higher trophic levels are not included

(iv) external costs of the use of insecticides have not (yet) been taken into account

(v) empirical data suggest the pest density in IPM to be significantly higher than modelled, resulting in a higher biological pest control losses and therefore higher losses of gross income and farm income

In general, the use of this approach allowed the researchers to address three pressing research needs: (i) to quantify the link between the loss of species and the provisioning of ecosystem services (biological pest control), (ii) to quantify the market value losses which can be attributed to the loss of relative species diversity and species abundance (iii) to objectively value the presence of natural predators both in species diversity and abundance based on their ecological role in the agroecosystem. Furthermore, the main aim of this research was to contribute to the supporting evidence for policy makers in choosing for biodiversity conservation based on the evidence of biodiversity benefits outweighing the opportunity costs incurred. The methodological framework applied allows for an objective standard to be applied, based on the ecological role of species within the agro-ecosystem, whereby a change in the biodiversity can be valued based on the changes in the provisioning of a marketable good. Future research will include the validation of the methodology for other species under different circumstances, involving more and other ecosystem services and trade-offs.

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